CONSTRUCTION AND TESTING OF A HYDROGEN LIQUEFIER

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CONSTRUCTION AND TESTING

OF A HYDROGEN LIQUEFIER

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CHAPTER I

INTRODUCTION

In general there are three temperature ranges of liquid baths for producing very low temperatures. Liquid air, oxygen, and nitrogen are used in the first temperature range - 90.2°K. (the normal boiling point of oxygen) to 63.3°K. (the triple point of nitrogen). The latter temperature can be obtained by reducing the pressure over liquid nitrogen. Liquid hydrogen has a normal boiling point of 20.4°K. but can be made to sublime as low as 10°K. under reduced pressure. The lowest temperature range is provided by liquid helium, which has a normal boiling point of 4.2°K. With the aid of a good vacuum pump, helium can be maintained at a temperature of 1°K.

The first temperature range is not difficult to obtain since liquid air, oxygen, and nitrogen are commercially available and can be shipped over a considerable distance by the use of vacuum containers. The liquefaction of helium in recent years has been made comparatively simple by a method, suggested by F. Simon[1], which uses liquid hydrogen as a refrigerant. Therefore, if liquid hydrogen is available, the liquefaction of helium may be rather easily carried out. Until recently,

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[1] Simon, F., Zeits. f. Ges. Kälte Ind., 39, 89, (1932); Simon, F., and Ahlberg, J. E., Zeits. f. Physik, 81, 816, (1933).

the liquefaction of hydrogen has been regarded as rather difficult, since it involved the use of complicated and expensive equipment. Consequently, very few laboratories installed low temperature equipment until widespread interest in cryogenic research resulted in the development of the small scale hydrogen liquefier which has a capacity of about one liter of liquid hydrogen per hour. This newer type hydrogen liquefier and the convential compressor-gasometer arrangement both utilize the Joule-Thomson effect and regenerative cooling, but differ in that the newer type uses commercially available compressed hydrogen in cylinders in place of a compressor.

This simplified hydrogen liquefier has the following advantages: (1) it is more economical for producing small quantities of liquid hydrogen, (2) it does not need specially trained attendants to operate apparatus, and (3) it is smaller, more compact, and portable. Although the compressor-gasometer system has a relatively high initial cost, it is more economical than the newer type for producing larger quantities of liquid hydrogen. This older type also has the advantage that all the unliquefied gas that is purified by passing through the liquefier is eventually liquefied. The disadvantages of the newer type are that 75 to 90% of the hydrogen which has been purified is lost and that the number of cylinders that can be used at one time is limited by the size of the purifier. The use of too many cylinders results in the passage of progressively more impure hydrogen to the liquefier, where the impurities freeze out and reduce heat transfer in the main heat interchanger.

The liquefier which has been built here incorporates the design

features described by a number of other experimenters.[2,3,4,5,6,7,8,9]

Our aim has been (1) to build a liquefier which is easily constructed and operated; (2) to design and construct a liquefier that contains two nitrogen precoolers, one of which operates at the normal boiling point of nitrogen and carries the main refrigeration load, enabling a vacuum pump of small capacity to be used for maintaining the second precooler near the triple point; (3) to use a regenerative exchanger which is more easily constructed than those previously used by other experimenters; and (4) to produce liquid hydrogen in quantities sufficient for producing liquid helium by Simon's expansion method.

Figure I (see Appendixes for all Figures) gives a front, over-all view of the apparatus. It is essentially composed of several compressed cylinders (on the extreme left), which supply high-pressure hydrogen of 99.8 to 99.9% purity; a purifier (left center), which adsorbs most of the impurities in gas; a liquefier (right center), which liquefies part

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[2] Latimer, W. M., J. Am. Chem. Soc., 44, 90, (1922).

[3] Latimer, W. M., Buffington, R. M., and Hoenshed, H. D., J. Am. Chem. Soc., 47, 1571, (1925).

[4] Bichowsky, F. R., J. Ind. Eng. Chem., 14, 62, (1922).

[5] Keyes, F. G., Gerry, H. T., and Hicks, J. F. G., Jr., J. Am. Chem. Soc., 59, 1426, (1937).

[6] Starr, C., Rev. Sci. Instruments, 12, 193, (1941).

[7] Ahlberg, J. E., Estermann, I., and Lundberg, W. O., Rev. Sci. Instruments, 8, 422, (1937).

[8] DeSorbo, W., Milton, R. M., and Andrews, D. H., Chem. Reviews, 39, 403, (1946).

[9] Fairbanks, H. A., Rev. Sci. Instruments, 17, 473, (1946).

of the hydrogen and collects the liquefied hydrogen within itself in the bottom of a glass Dewar vessel; and a transfer system by which the liquid is removed from the liquefier.

High-pressure hydrogen from a number of cylinders, which are connected bya manifold, passes directly to the purifier. In Figure 3 it can be seen that the impure high-pressure hydrogen gas enters the purifier at "a", passes through a silica gel trap "s" at room temperature and emerges at "b". The gas then passes to "c" by means of a jumper (not shown), where it is conducted through the interchanger I, before entering the first of the three charcoal traps, which are cooled in liquid nitrogen and connected in series. Having passed the purifier, the hydrogen is conducted through a valve and a second manifold before it enters the liquefier. As is seen in Figure 8, the high-pressure hydrogen enters the liquefier at HP and passes in turn through the external heat exchanger E1, the heat exchanger E2, the cooling coil F1, the heat exchanger E3, the cooling coil F2, the main heat exchanger X (regenerative exchanger), and the expansion valve V. After expansion, the cold low-pressure hydrogen gas is conducted in countercurrent flow through the various exchangers outlined above until it emerges at EL. Finally, this gas is passed through a flow meter before being discharged to the atmosphere.

CHAPTER II

THE PURIFIER

The compressed, electrolytic hydrogen gas which was supplied by the National Cylinder Gas Co., Atlanta, Georgia, had a purity of 99.8 to 99.9% - the chief impurities being oil, water vapor, nitrogen, and oxygen. The removal of the impurities is essential for trouble-free operation of the liquefiers which are built to operate by using commercial hydrogen in cylinders as a source of high-pressure gas. The purifier which has been built here is designed to remove these impurities by passing the high-pressure gas over silica gel at room temperature and over activated charcoal, cooled to 77.3°K. by means of a bath of liquid nitrogen.

This purifier, complete, is shown in Figure 3. Figure 4 gives a detailed view of the design of the silica gel and charcoal traps proper. Details of construction are given in Appendix A.

Most of the oil and water vapor in the high-pressure hydrogen is removed by the silica gel trap. The three charcoal traps remove practically all of the remaining water and oil vapor, the oxygen, and most of the nitrogen.

The nitrogen is the impurity that is difficult to remove completely. With a constant flow rate of 5 cubic feet per minute, roughly 380 gram moles of high-pressure gas enter the liquefier per hour. If this gas contains 0.01 mole percent of nitrogen (solid nitrogen having a density of 1.026 grams per cc[10]) about 1 cc of solid matter will separate in the

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[10] I. C. T., Vol. I, 104, (1926).

small, high-pressure tube of the regenerative exchanger per run. The following information is given by Blanchard and Bittner. [11] A properly designed throttling valve will usually pass a considerable amount of solid matter without too much plugging. However, another great difficulty arises from the fact that the condensing impurities have some tendency to plate-out as a coating of high thermal resistance on the walls of the high-pressure tubes. This plating-out seriously reduces the efficiency of heat exchange between the low- and high-pressure streams. In extreme cases, freezing impurities may produce constrictions sufficient to cause a portion of available Joule-Thomson expansion to occur at the wrong places. Thus, the liquefier usually suffers a progressive decrease in efficiency of liquefaction with time of operation. This gradual decrease in efficiency may go unnoticed since the liquefier may appear to be working smoothly by every other indication.

The charcoal traps are immersed in a bath of liquid nitrogen contained in a metal Dewar vessel which is sufficiently long to extend about one inch above the topmost coil of interchanger I. In the interchanger the warm gas, leaving the silica gel trap, is interchanged with the cold purified gas, leaving the third charcoal trap. When operating with flows of 4 to 5 cubic feet per minute (CFM), the gas emerges from the interchanger at about 15°C. below room temperature.

After being used, the silica gel and charcoal traps need to be reactivated by the removal of adsorbed gases and vapors. The tube con-

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[11] Blanchard, E. R., and Bittner, H. W., Rev. Sci. Instruments, 13, 394, (1942).

necting the two traps, between "b" and "c", is removed by unscrewing the compression fittings. Activation is then carried out by simultaneously pumping at "b" and "c" ("a" and "d" being closed off), using a small vacuum pump protected by a trap cooled with liquid nitrogen. Both the silica gel and charcoal traps (enclosed, respectively, in a stationary heater and a removable furnace) are heated to 140 to 150°C. for several hours at a pressure of about 10^{-1} mm. mercury (absolute). The temperature is controlled by variable resistances and thermocouples. After the traps have been cooled to room temperature, the vacuum is broken by admitting hydrogen gas from the cylinders.

CHAPTER III

THE LIQUEFIER

The hydrogen liquefier which has been built here is a compact, relatively portable unit so designed that its principal parts are readily accesible for inspection and repairs. The assembled liquefier occupies a floor space of 14" x 23" and is 48" tall. Figures 5, 6, and 7 show, respectively, the assembled liquefier (rear view), the control panel, and the liquefier proper. Details of construction are given in Appendix B.

Figure 8 represents a schematic detail of the liquefier. Briefly the liquefier consists of two pots (N1 and N2) for the liquid nitrogen which is used as the refrigerant; four heat exchangers (E1, E2, E3, and X); two cooling coils (F1 and F2); four thermocouples (T1, T2, T3, and T4); and the expansion valve V. The liquid hydrogen produced is collected in the bottom of the glass Dewar vessel J and can be transferred therefrom through the vacuum-jacketed transfer system HT, which extends to the bottom of this vessel.

The two nitrogen pots operate at different temperature levels. Pot N1, which is filled through K and has a vent R, is operated at 77.3 ^{o}K., the normal boiling point of liquid nitrogen. The liquid nitrogen in pot N2, which is admitted to pot N2 from pot N1 by valve NV operated by the valve stem O, is made to boil under reduced pressure at 66^{o}K. by means of a vacuum pump (Welch Duo-Seal No. 1400B, 21 liters per minute free air capacity), connected at L.

The liquid level in pot N1 is controlled by the thermouples T1

and T2 so that it remains between these two couples. Thus, the liquid is always kept below heat exchanger E2, while the cooling coil F1 is always immersed in the refrigerant. The space between T1 and T2 has a volume of 350 cc.

The liquid level in pot N2 is not directly measurable. However, the level can be regulated sufficiently well by the thermocouple T3, which is soldered externally to the pot and by the behavior of the vacuum pump. This pot has a volume of 300 cc.

The thermocouple T4, soldered to the body of the expansion valve V, permits the temperature of V to be followed. About one liter of liquid hydrogen can be collected in J before the liquid level reaches the expansion valve.

The space between the bottom of pot N2 and the lowest coil of the exchanger X was packed loosely with woolen blanket cloth. This insulation has been found to prevent diffusion or convection of the cold low-pressure hydrogen into the higher temperature zones before it passes through the exchanger. Failure to do this packing results in a very decided decrease in the efficiency of liquefaction.[7]

The space between the bottom of N1 and the top of N2, the space between the brass dome W and the outside surface of N1 in the region of the heat exchanger E2, and the space surrounding the heat exchanger E1 were all packed with this same material. It is of considerable importance that the outside surface of the upper part of pot N1 be insulated since the Dewar vessel does not extend into the brass dome. Even with insulation, a great deal of moisture condenses on the outside surface of the brass dome. If the liquid level in pot N1 is allowed to be much above

thermocouple T1, this moisture is frozen.

The high- and low-pressure lines connecting E1 and E2 were also wrapped with this insulating material, which prevents frosting during operation. With insulation the low-pressure hydrogen leaves E1 at 5 to 10°C. below room temperature.

The expansion valve, the valve NV, and the transfer valve require special construction since they operate at low temperatures, be externally adjustable, be small in size, and have delicate control. The expansion valve, in addition, must operate with a pressure on the high side of 136 atmospheres and on the low side of about 1.5 atmospheres. After expansion the liquid and gaseous hydrogen pass through copper turnings, which tend to keep liquid hydrogen from entering exchanger X as a mist.

A number of controls for operating the liquefier, as well as for diagnosing troubles, are provided. Measurements of the pressure of the high-pressure hydrogen are made at the second manifold, before the hydrogen enters exchanger E1, and at a point G2, just before the cold gas enters the expansion valve. During operation with flow rates of 3 to 5 CFM, there exists no appreciable pressure drop across these points. A third gauge, G3, measures the hydrogen pressure after expansion in the Dewar vessel. This pressure in normal operation is 7 to 12 pounds per square inch (psi). The Dewar is protected by a safety valve (not shown) which is set for 50 psi.

A bourdon-type vacuum gauge in the pumping line L to pot N2 permits the pressure in the lower pot to be measured and thus the temperature to be obtained. A Kerotest diaphragm-type valve in the pumping line allows the pressure in this pot to be maintained at the desired.

value.

Provision has also been made for thawing out both the expansion valve V and the heat exchanger X in case of freezing impurities. This thawing-out is accomplished by directing a stream of warm gas against the body of the expansion valve. This gas, controlled by a valve at the second manifold (Figure 2), is admitted to the liquefier through a 0.040" O.D. x 0.010" wall cupro-nickel capillary tube (visible in Figure 7 but not shown in Figure 8), which passes along the outside of both nitrogen pots. This device is of great help for rapidly warming the expansion valve and exchanger X. An almost immediate response is indicated by thermocouple T4. The small heat capacity of the parts involved permits a rapid return to hydrogen liquefier conditions when expansion is resumed.

Low-pressure, outgoing hydrogen is heated by high-pressure, incoming hydrogen at all liquefier temperature levels by exchangers (E1, E2, E3, and X) until room temperature is almost reached. The cooling which is not produced by exchangers (E1, E2, and E3) is accomplished by the nitrogen pots. These exchangers determine only the rate and thus the quantity of liquid nitrogen used. The regenerative exchanger X determines the regenerative cooling and thus the efficiency of the liquefaction process. Therefore, exchangers (E1, E2, and E3) are not as important as exchanger X. It is obviously desirable that the efficiency of the heat exchangers be as high as possible. This efficiency has been well defined as the ratio of the actual temperature rise of the outgoing gas between the two ends of the exchanger to the maximum possible temperature rise. This is approximately the ratio of the actual amount of heat exchanged between the two gas streams to the maximum possible.

The following information on heat exchangers follows closely that given by Starr. [6] The regenerative exchanger should have an efficiency of at least 95%, and all others should not be below 90%. The drop in pressure through both sides of the exchangers should be low in order to maintain high efficiency of liquefaction. Excessive pressure drop in the high-pressure side of the regenerative exchanger results in Joule-Thomson cooling along the exchanger, and this self-cooling reduces the heat exchange with outgoing gas by reducing the temperature difference. Excessive pressure drop in the low-pressure side raises the pressure in the liquid hydrogen chamber and reduces the efficiency of liquefaction by causing liquefaction at both a higher temperature and pressure. Low- pressure in the hydrogen chamber is also desired for structural reasons.

A pressure drop of not more than 0.8 atmosphere from the liquid hydrogen chamber to the outlet is satisfactory. Most of the pressure drop occurs in the high temperature portion of the exchanger system, the exchanger X contributing a drop of only .1 to .2 atmosphere. Under these described conditions the temperature of the high-pressure hydrogen before expansion is about 42 to 46°K. (Appendix C). Therefore, there is no liquid hydrogen formed in the high-pressure side of the exchanger since the critical temperature of hydrogen is 33.3°K.

The shortness and compactness of the "twisted tube" exchanger (a type of regenerative exchanger) has made it possible to use this kind of a hydrogen liquefier. From some experiments carried out at Johns Hopkins University* it has been observed that with a flow-rate of about 3 CFM an exchanger of this type of 22" in length gave the same lique-

faction efficiency as one of 62" in length in the operation range of 2000 to 600 psi. However, this type of exchanger is quite difficult to construct. On account of ease of construction the flat tube exchanger used in the work was designed to replace the "twisted tube." The construction of the flat tube and "twisted tube" exchangers is given in Appendix B.

CHAPTER IV

OPERATING CHARACTERISTICS OF LIQUEFIER

Three runs of varying length were made (July 3, July 25, and August 1) with this liquefier. The purpose of the first run was to familiarize the operators with apparatus and to verify the fact that the liquefier would produce liquid hydrogen. The efficiency of liquefaction was not measured until the July 25 and August 1 runs.

From an analysis of the first three runs, the composite run is given in Table I, page 21. The production rate is essentially that observed on the August 1 run.

The liquefier has given trouble-free performance except when impure gas was used. The expansion valve has needed only occasional adjustment as the pressure in the cylinders fell. The hydrogen transfer system has worked smoothly. The consumption of nitrogen has not been excessive. After liquefaction had begun, the upper pot N1 required filling every 12 to 15 minutes: and the lower pot N2 required filling once an hour.

The rate of production of liquid hydrogen was measured as follows: The liquefier was first drained of all liquid hydrogen: then it was allowed to run for a period of 20 to 30 minutes. At the end of this time the liquid hydrogen was transferred from the liquefier through the transfer valve to a deep Dewar vessel which already contained liquid hydrogen from a previous transfer. The hydrogen transfer tube is a double walled, vacuum-jacketed tube constructed of cupro-nickel alloy. The inner tube is provided with a vacuum-jacketed needle valve, oper-

ating from valve stem on top of liquefier. Upon opening the transfer valve, the liquid hydrogen was forced through the transfer system by the excess of pressure (7 to 12 psi) on the liquid in the bottom of the liquefier to the external Dewar vessel. The increase in the height of the liquid level in this external Dewar vessel was measured by means of a thermocouple probe, surrounded by an electrical heater. By means of the probe, the liquid level was measured to within 1/8". The production rate quoted in the summary of Table I was measured in like manner. The actual production rate in the liquefier is somewhat greater than that measured in this manner because of heat leaks, possible mist formation, and pressure drop losses during transfer from liquefier. With a pressure drop of 12 psi about 8% of liquid is lost (Appendix C).

The actual efficiency of liquefaction was calculated from the volume of liquid hydrogen collected and the drop in pressure in cylinders during the same period. This calculation is given on page 35. The details of the calculation of theoretical efficiency are given in Appendix C.

During these runs the lower nitrogen pot was kept at a temperature of 66°K. The actual average efficiency for the August 1 run in the ranges of 1880 to 1520 psi and 1520 to 1100 psi was found to be respectively 4.4 and 4.5%.* If transfer losses are taken into account, these efficiencies of liquefaction should be raised to perhaps 6 to 8%. The theoretical efficiencies of liquefaction in these pressure ranges are

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* Since the August 1 run, the flat tube exchanger has been replaced by a "twisted tube" exchanger. A summary (Sept. 22 run) with this later exchanger is given as a comparison. See page 21.

26 and 24% when T = 66°K.** and 17 and 15% when T = 77.3°K.

The large difference between the actual and theoretical efficiency of liquefection may be due to several causes:

(a) The transfer loss may be larger than estimated.

(b). The gas reaching the top of the regenerative interchanger from the lower precooler may be warmer than the 66°K. used for the efficiency calculations: that is, the lower precooler coil F2 may be too short.

(c) The efficiency of the regenerative interchanger may be low.

These three causes will now be briefly analyzed.

The transfer loss can be evaluated if the gaseous hydrogen produced during transfer is metered, since this will measure the amount of liquid hydrogen lost, both due to heat losses in the transfer system and to possible mist formation. Since no such measurements were made, it is not possible to evaluate the transfer loss exactly.

In order to analyze the possible inefficiency occurring under items (b) and (c), the Reynold's number of the high pressure hydrogen passing through the lower precooler coil F2 and the regenerative exchanger X was calculated for the various operating conditions used. These calculations together with graphs giving the viscosity of hydrogen gas as a function of temperature and pressure are given in Appendix F. It was found that under all operating conditions the Reynold's number was above 10,000 (Figure 4), indicating that the flow in both F2 and X is turbulent

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** T = represents the temperature of hydrogen entering regenerative exchanger.

rather than streamlined flow.

Cooling coild F1 and F2 constructed of copper tubing operate by transferring heat from the turbulent high-pressure hydrogen gas to boiling liquid nitrogen. Since coil F1 to 14 feet long, it is believed that the high pressure gas leaving pot N1 should be very close to 77.3°K. Coil F2 is only 5.3 feet in length but has only to cool the hydrogen from 77.3°K. to 66°K. On the other hand, the regenerative interchanger is only 30 inches long and suffers the disadvantage of being constructed of a poor thermal conductor, namely Super-nickel alloy, though the wall thickness of the tubing used is only 0.010 inches. Furthermore, the heat exchange is the regenerative interchanger involves heat transfer between two turbulent gas streams.

It was not possible to separate satisfactorily the possible inefficiencies occurring in F2 and X. However, since this work was completed, the flat-tube regenerative exchanger has been replaced by a "twisted-tube" exchanger of the same material and length as X, all other parts of the liquefier being kept the same. With this single change the efficiency of liquefaction has been raised from 4.4 to about 10%.

This latter work strongly suggests that the reason for the poor performance of the liquefier described in this thesis lies in the inefficient operation of the flat-tube regenerative exchanger.

From this result alone it is still not possible to determine how much of the remaining inefficiency lies in the cooling coil F2 and how much is either the result of poor performance for the regenerative heat exchanger or the result of transfer losses. Measurements of the actual

transfer losses together with a measurement of the temperature of the high-pressure hydrogen reaching the top of the regenerative exchanger are planned and should aid in settling these questions.

On all runs with the apparatus the cylinders were replaced when the pressure got as low as 500 to 600 psi. It is not economical to operate with pressures much lower than this as the efficiency of liquefaction falls rapidly with lower pressure as seen on Figure 1. This efficiency of liquefaction is expected to be still lower because of the more rapid velocity of gas through exchanger X, which reduces heat exchange and thus exchanger efficiency. The cylinders were also found ti contain liquid water in the bottom. As the pressure of hydrogen in the cylinders decreases, the concentration of water vapor in gas increases, which causes purification difficulties.

The apparatus for measuring liquid hydrogen consisted of a brass case, containing a glass Dewar flask, 3-1/8" I.D.; a rubber stopper; an electrically heated thermocouple probe; and a double-walled vacuum glass tube. The rubber stopper, having two holes through which passed the glass tube and probe (surrounded by short piece of pressure tubing), fits into the Dewar flask. Details of construction of probe are given in Appendix D.

When the probe was above the liquid level, the heater kept the thermocouple well above the liquid hydrogen temperature. Once the thermocouple touched the liquid, a rapid deflection of potentiometer was observed. Thus the liquid level could be located. However, the probe did not give a direct measurement of liquid depth, since the height of probe was measured from rubber stopper to top of probe.

The flow meter is an orifice calibrated for two plates using a manometer filled with colored water. The meter is not accurate enough for calculating efficiency of liquefaction (explained in Appendix C) but is extremely useful for keeping flow through the liquefier steady and for obtaining a very good estimate of flow.

TABLE I

COMPOSITE RUN OF HYDROGEN LIQUEFIER

Time (hours)	Operation
0.0	Three tanks on at 800 psi. Began cooling charcoal traps of purifier with liquid nitrogen.
.25	Began transfer of nitrogen to pot N1.
.27	Charcoal traps at liquid nitrogen temperature (4 liters required to cool and fill metal Dewar surrounding charcoal traps).
.43	Began slow flow of hydrogen through liquefier (1 CFM).
.50	Began transfer of liquid nitrogen to pot N2.
.70	Both pots full (2.0 liters liquid nitrogen required). T4 reads 1.13 millivolts.
.80	Hydrogen flow increased to 2 to 3 CFM.
1.44	T4 reads 6.8 millivolts, liquefaction of hydrogen began. Cylinder pressure-- 300 psi.
1.53	Cylinders replaced by three cylinders with 1800 psi. Flow rate increased to 4 to 5CFM.
2.65	Cylinder pressure-- 750 psi.
3.05	Cylinders replaced by three cylinders with 1930 psi. Pressure in expansion chamber-- 9 psi.
3.09	Liquid hydrogen transfer ended. Pressure-- 1880 psi.
3.42	Liquid hydrogen transfer ended. Pressure-- 1520 psi.
3.79	Liquid hydrogen transfer ended. Pressure-- 1100 psi.
4.67	Pressure in cylinder-- 605 psi. Run stopped.

TABLE I (cont.)

Summary (August 1 run)

Production Rate-- 0.43 liters per hour at 4 to 5 CFM.

Consumption of liquid nitrogen

(1) To cool charcoal traps-- 4 liters

(2) To cool liquefier to hydrogen temperature of liquefaction-- 3 liters

(3) To produce 0.7 liter liquid hydrogen

(a) Purifier-- 3.9 liters

(b) Liquefier-- 5 liters

Total liquid nitrogen consumption-- 15.9 liters

The summary of the following run of September 22 is given as a comparison of both types of exchangers used:

Summary (Sept. 22 with "twisted tube")

Total volume of liquid hydrogen produced-- 1.5 liters.

Production rate-- 0.75 liters per hour at 3 to 4 CFM.

Liquid hydrogen produced per set of three cylinders (1900 to 700 psi.)-- 0.9 liter.

Consumption of liquid nitrogen

(1) To cool charcoal traps-- 6.2 liters

(2) To cool liquefier to hydrogen temperature of liquefaction-- 3.0 liters

(3) To produce 1.5 liters liquid hydrogen.

(a) Purifier-- 4.7 liters

(b) Liquefier-- 4.4 liters

Total liquid nitrogen consumption-- 18.3 liters.

BIBLIOGRAPHY

Ahlberg, J. E., Estermann, I., and Lundberg, W. O., Review of Scientific Instruments, 8, 422, (1937).

Bichowsky, F. R., Journal of Industrial Engineering Chemistry, 14, 62, (1922).

Blanchard, E. R., and Bittner, H. W., Review of Scientific Instruments, 13, 394, (1942).

Deming, W. E., and Shupe, L. E., Journal of American Chemical Society, 53, 843, (1931).

DeSorbo, W., Milton, R. M., and Andrews, D. H., Chemical Reviews, 39, 403, (1946).

Dodge, B. F., Chemical Engineering Thermodynamics, McGraw-Hill Book Company, Inc., New York, N.Y., 1944, pp. 417-482.

Fairbanks, H. A., Review of Scientific Instruments, 17, 473, (1946).

International Critical Tables, vol. I, 2, 102, (1926).

Johnston, H. L., and McCloskey, K. E., Journal Physical Chemistry, 1038, (1940).

Keesom, W. H., and Houthoff, D. J., Communications from the Physical Laboratory of the University of Leiden, Suppl. No. 65, (1928).

Keyes, F. G., Gerry, H. T., and Hicks, J. F. G., Jr., Journal of American Chemical Society, 59, 426, (1937).

Landolt-Börnstein, Physiklisch-Chemische Tabellen, Eg. I, 144-148, (1927).

Ibid., Eg. IIa, 140-144, (1931).

Ibid, Eg. IIIa, 187-189, (1935).

Latimer, W. M., Journal of American Chemical Society, 44, 90, (1922).

Latimer, W. M., Buffington, R. M., and Hoenshel, H. D., Journal of American Chemical Society, 47, 1571, (1925).

Perry, J. H., Chemical Engineers' Handbook, McGraw-Hill Book Company, Inc., New York and London, 789-796, (1941).

Simon, F., Zeitschrift für die gesamte Kälte-Industrie, 39, 89, (1932).

Simon, F., and Ahlberg, J. E., Zeitschrift für Physik, 81, 816, (1933).

Starr, C., Review of Scientific Instruments, 12, 193, (1941).

Walker, W. H., Lewis, W. K., McAdams, W. H., and Gilliland, E. R., Principles of Chemical Engineering, McGraw-Hill Book Company, Inc. New York and London, 56-68, (1937).

APPENDIX A

DETAILS OF CONSTRUCTION OF PURIFIER

All tubing used, unless otherwise noted, was 3/16" O.D. x 0.035" wall, dead-soft temper copper tubing. Either standard SAE flare fittings or brazed (Easy-Flo) joints were used for construction. The interchanger I consists of twelve turns of this copper tubing, constructed by soft-soldering side by side two 11.5 feet lengths. The interchanger was then wound on a 3-7/16" diameter mandrel.

The cylindrical metal Dewar vessel is 23-1/2" deep and has an inside diameter of 4-1/4". It was specially constructed for this project by the Hofman Laboratories, 212 Wright Street, Newark, N. J. It shows an evaporation rate of .125 pounds of liquid nitrogen per hour when half filled.

The detailed design of the charcoal and silica traps is shown in Figure 4. The construction of the traps differs in that the silica gel trap is 32" long instead of 12" long. All parts of the trap, with the exceptions of the copper inlet and exit tubes "A" and the brass screens "ST" and "SB", are of monel. All joints were brazed using "Easy-Flo" silver brazing alloy. The tube "M" was constructed of 1.75" x 0.22" wall (No. 5 gauge) normalized cold drawn, seamless monel tubing. The threaded monel plugs, "ET" and "EB" (24 threads per inch), were made of hot rolled monel. The screens "ST" and "SB" were constructed of 1/32" brass sheets drilled with numerous 1/64" diameter holes. They are held in place by peening over the edge of the recess provided in the plugs "ET" and "EB", respectively. The screens are intended to prevent the charcoal (or silica gel) from leaving the trap, while permitting free passage of gas.

After brazing, each trap was hydraulically tested to 5,000 psi with the use of oil. The average increase in diameter at this pressure was 0.0005". No oil leaks appeared, and no permanent set was observed. After the test the cap "c" was cut off the filling tube "T" (3/8" O.D. x 0.065" wall monel), and the trap was thoroughly cleaned with carbon tetrachloride. The trap was then filled with either 119 grams of activated charcoal (Columbia Activated Carbon, Grade 6G, 8/14 mesh, obtained from Carbide and Carbon Chemical Corp., New York, N.Y.) or 522 grams of activated silica gel (Commercial grade, Type 3, obtained from Davison Chemical Corp., Baltimore, Md.). The adsorbent was introduced through the filling tube "T" which passes through the screen "ST". The cap "c" was then replaced and sealed with Easy-Flo.

The hydraulic testing unit used consisted of a hydraulic press (Blackhawk Jack Model No. 76, made by Blackhawk Mfg. Co., Milwaukee, Wis.) and a 10,000 psi Ashcroft pressure Gauge (Duro-gauge type 1077) joined to the manifold by standard SAE copper flare fittings and 1/4" O.D. x 0.035" wall soft copper tubing. The pressure gauge was protected by an Ashcroft gauge saver (type 1073), which dampens severe pressure pulsations.

Each trap was filled with hydraulic fluid before it was connected to the manifold by pulling a continuous vacuum on the trap, which was accompanied by a simultaneous filling with oil. The trap was then sealed at one end, and the other was connected to the manifold with a flare fitting. Thus the complete system was filled with fluid except for the air needed to prevent oil from getting to gauge.

The silica gel trap (Figure 3) is provided with a 44 ohm bare

nichrome wire (No. 22) heater, "H1" and "H2", wound onto a thin-walled brass tube but separated from it by a layer of electrically insulated cement (Sauereisen Insa-lute Cement No. 1). The trap was placed inside the heater tube; then the heater was thermally lagged with asbestos. For the charcoal traps, a removable furnace was built into which the trap assembly fits. The furnace was a brass shell-- covered with a layer of cement, wound with a nichrome heater wire, and insulated with 1/4" layer of asbestos.

APPENDIX B

DETAILS OF CONSTRUCTION OF LIQUEFIER

The materials of construction consist primarily of cupro-nickel*, copper, and brass tubing. All tubes passing through the brass end plates-- designated as AA, BB, CC, and DD in Figure 8-- with the exception of the copper high- and low-pressure lines, are cupro-nickel. The two nitrogen pots were made of 70% copper, 30% nickel alloy material.** Longitudinal strains were minimized and the low thermal conductivity of this alloy used to advantages.

All joints and seals were made with the use of either 60% lead, 40% tin solder, or "Easy-Flo" silver brazing alloy. All joints at Section AA, BB, CC, and DD were soft soldered with the exception of the joint between plate DD and N2, which was brazed. All joints in the high-pressure hydrogen circuit were brazed and tested for leaks at 2000 psi before final assembly. The joints in the low-pressure hydrogen line are for the most part made with soft solder. The joint between the brass tube which surrounds the Dewar vessel and the plate which supports the liquefier (compare Figures 5 and 7) is soft solder seal. This seal can be broken quite easily by heating the joints simultaneously with two small air-gas hand torches.

The first regenerative exchanger, the only exchanger used by the author, was designed to combine simplicity, low heat capacity, and good

---

* 30% Ni, 70% Cu-- obtained from Superior Tube Co., Norristown, Pa.

** Made available to us by Dr. D. H. Andrews, The Johns Hopkins University, to whom we wish to express our thanks.

efficiency. Unfortunately, its efficiency was found to be very low, and it has since been replaced by a "twisted tube" exchanger. Figure 7 shows the first used regenerative exchanger. Figure 8 represents a cross-sectional view of the second regenerative exchanger X.

The first exchanger X was made by soft-soldering a flattened 1/8" O.D. x 0.010" wall cupro-nickel tube 30 inches long (thickness after flattening was 0.061") between two round tubes of the same kind. This construction was also used for the two turn exchanger E3.

The second exchanger X was modeled after the so called "twisted tube" exchanger of Nelson[4], which has been used successfully by others. This present design is modeled after one proposed by Mr. William Asher of the Johns Hopkins University Low Temperature Laboratory. The twisted tube, which constitutes the high-pressure side of the exchanger was made by first flattening a 1/8" O.D. x 0.010" wall, well annealed cupro-nickel tube to a thickness of 0.088" for a length of 30 inches by passing it through a set of hand rolls. About 3 inches were left round on each end, and the ends were soft soldered to brass plugs. The plugs were then clamped between the lead and tail stocks of a lathe. The flattened portion of the tube was then twisted to give a spiral form with a pitch of 20 turns per foot. Pieces of 1/32" 50-50 solder wire were wrapped in the grooves of the spiral, a light coat of flux paste applied, and the whole slipped into a 3/16" O.D. x 0.016" wall, well annealed cupro-nickel tube which served as the outside wall of exchanger. The length of the 3/16" tube was such that the spiral portion protruded about 1/4" on each end in order to reduce the pressure drop which might be present if the round section of the 1/8" tube came to the ends. The assembly was

then heated in a tube furnace to about 220°C., turned in vertical position, and the excess solder and flux forced out by applying a low pressure of nitrogen gas. This was followed by a thorough wash with carbon tetrachloride, water, and acetone to remove all flux. The assembly was then wound on a 2-1/8" mandrel.

APPENDIX C

(A) THEORETICAL CALCULATION OF LIQUEFACTION EFFICIENCY

The theoretical efficiency of liquefaction curve is shown in Figure 1. Assuming no heat loss and that T_1 is equal to T_3, by following Dodge[12] it is easy to show that

$$e = \frac{H_3 - H_1}{H_3 - H_2} \qquad (1)$$

where e-- fraction of entering hydrogen collected as liquid

H_1-- enthalpy of hydrogen gas leaving pot N2 and entering regenerative exchanger

H_2-- enthalpy of liquid hydrogen in bottom of liquefier

H_3-- enthalpy of gas leaving regenerative exchanger and entering pot N2

T_1-- temperature of gas with H_1

T_2-- temperature of gas with H_3

All enthalpies (H_1, H_2, etc.) were read off a temperature entropy diagram of Keesom and Houthoff[13] with units of calories per gram (enthalpy of liquid hydrogen at 1 atmosphere and 20.4°K. equal to 0). With cylinder pressure of 2000 psi and T_1 of 77.3°K., assuming pressure of 1 atmosphere after expansion, e is easily calculated by using Equation (1).

---

[12] Dodge, B. F., Chemical Engineering Thermodynamics, McGraw-Hill Book Company, Inc., New York, N.Y., 1944, pp. 417-482.

[13] Keesom, W. H., and Houthoff, D. J., Comm. Phys. Lab. Univ. Leiden, Suppl. No. 65, (1928).

$$e = \frac{252 \text{ cal/gm} - 206 \text{ cal/gm}}{252 \text{ cal/gm} - 0 \text{ cal/gm}} = 0.183$$

$\therefore$ Theoretical efficiency of liquefaction-- 18.3 %

(B) CALCULATION OF CONDITION OF GAS ENTERING EXPANSION VALVE

With the same assumptions and conditions, the following Equation is obtained:

$$H_4 = e\,H_2 + (1 - e)\,H_{2'} \qquad (2)$$

where H_4-- enthalpy of gas entering expansion valve

H_2-- enthalpy of liquid hydrogen in bottom of liquefier

$H_{2'}$-- enthalpy of hydrogen gas in equilibrium with liquid

Using Equation (2) with values

$$H_4 = 0.181\ (0 \text{ cal/gm}) + 0.817\ (104 \text{ cal/gm}) = 85 \text{ cal/gm}$$

Hydrogen with pressure of 2000 psi and enthalpy of 85 cal/gm has a temperature between 45 and 46°K.

(C) TRANSFER LOSS DUE TO PRESSURE DROP

If the liquid in liquefier were at a pressure of 12 psi (gauge), the loss in liquid due to drop in pressure across transfer valve can easily be calculated, assuming no heat leaks. The following equation is the same as Equation (2) representing different conditions.

$$H_5 = f\,(H_6) + (1 - f)\,H_7 \qquad (3)$$

where f-- fraction of liquid that becomes gas after expansion

H_5-- enthalpy of liquid hydrogen at 12 psi gauge

H_6-- enthalpy of liquid hydrogen after expansion (1 atm. absolute)

H_7-- enthalpy of liquid hydrogen after expansion

Using values in Equation (3)

$$8 \text{ cal/gm} = f\,(104 \text{ cal/gm}) + (1 - f)\,0 \text{ cal/gm}$$

$$f = \frac{8}{104} = 0.077$$

∴ 7.7 % of liquid in liquefier is lost due to only Joule-Thomson expansion.

(D) CALCULATION OF ACTUAL EFFICIENCY OF LIQUEFACTION

The liquid hydrogen from liquefier was transferred to a glass Dewar vessel of 3-1/8" I.D., giving a volume per inch of

$$\text{Vol/in} = \frac{(3.125)^2}{4}\ \text{in}^3 \times \frac{(2.54)^3\ \text{cc}}{\text{in}^3}$$

$$= 125.8 \text{ cc/in.}$$

After transferring all liquid hydrogen in liquefier and measuring level inside Dewar vessel, the liquid hydrogen was collected for 19.5 minutes with a pressure drop from 1880 to 1520 psi in cylinders. The liquid was then transferred; this gave a rise inside Dewar of 1-1/8".

The volume collected is easily calculated

(a) Vol. = 1-1/8" x 125.8 cc/in = 141.4 cc liquid

The density of liquid hydrogen is 0.0709 gm/cc.[14] The compressibility factor for hydrogen gas at 1 atmosphere and 25°C. (Figure 9) is 1.019. Therefore the volume of gas at 1 atm. and 25°C. from 1 cc of liquid is

Vol = 1 cc x 0.0709 gm/cc x 1b/453.6 gms x 1b mole/2.016 lbs
x 359 CFM/1b mole x 1.091
= 0.0304 ft^3 gas/cc liquid

Thus the 141.5 cc of liquid, converted to gas (1 atm, 25°C.), would be

Vol = 141.5 cc x 0.0304 ft^3 gas/cc = 4.03 ft^3

As can be seen in Figure 10, a cylinder (P-- 1880 psi, T-- 25°C.) would hold 182 ft^3 (P-- 1 atm, T-- 25°C.). A cylinder (P-- 1520 psi, T-- 25°C.).would hold 149.5 ft^3 (P-- 1 atm, T-- 25°C.). Thus a cylinder dropping in pressure from 1880 to 1520 psi would give a volume of

Vol = 182 - 149.5 = 32.5 ft^3/ cylinder

Three cylinders would give

32.5 ft^3 x 3 = 97.5 ft^3

---

[14] I. C. T., vol. I, 102, (1926).

(b) $\therefore$ Efficiency of liquefaction $= \frac{4.03}{97.5} \times 100 = 4.4\ \%$

141.5 cc were collected over an interval of 19.5 minutes. Thus the production rate per hour is

(c) $\frac{141.5\ cc}{19.5\ min} \times \frac{60\ min}{hour} = 435\ cc/hour$

The flow meter over this period gave a constant reading of 4.5 CFM (P-- 1 atm, T-- 25°C.). The unliquefied gas was thus

$$4.5\ ft^3/\ min \times 19.5 = 87.8\ ft^3$$

The difference between volume leaving cylinders and volume unliquefied is volume liquefied.

$$97.5\ ft^3 - 87.8\ ft^3 = 9.7\ ft^3$$

(d) $\therefore$ Efficiency of liquefaction $= \frac{9.7}{97.5} \times 100 = 9.9\ \%$

The efficiency of liquefaction based on the flow meter is not very accurate as the error in flow is greatly increased upon multiplying by time. Thus, an error of only 0.1 CFM will change the efficiency by 2 %. The efficiency based on Dewar measurements is also somewhat inexact, because of neglecting of hydrogen in line between cylinders and gauges (small error) and because of the error in use of probe. The efficiency in (b) should be less than (d) on account of losses in transfer.

Figure 1

Theoretical Efficiency of Liquefaction

A plot of theoretical efficiency against pressure in cylinders along constant temperature lines (T_{N2}) of operation of lower nitrogen pot. The data of Johnston, H. L., and McCloskey, K. E., J. Phys. Chem., 1038, (1940); and Keesom, W. H., and Houthoff, D. J., Comm. Phys. Lab. Univ. Leiden, Suppl. No. 65, (1928), were used.

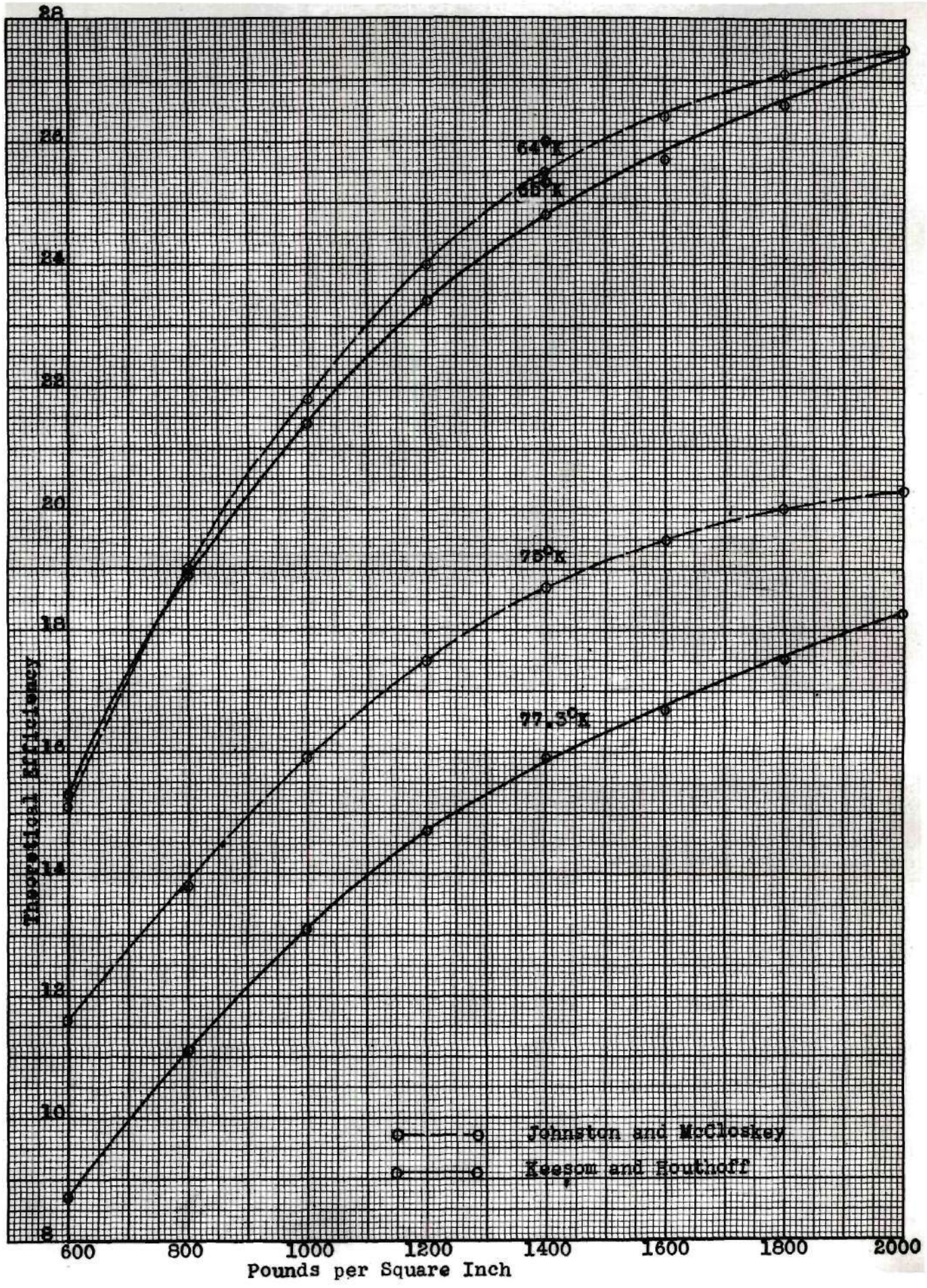

Theoretical Efficiency
Pounds per Square Inch
64°K
65°K
75°K
77.3°K
Johnston and McCloskey
Keesom and Bouthoff

TABLE II

Pressure	T_{N2} -- 77.3°K.		T_{N2} -- 65°K.	
psi	e	T_4 in °K.	e	T_4 in °K.
2000	0.183	45-46	0.275	42-43
1800	.175		.266	
1600	.167	45-46	.257	42
1400	.159		.248	
1200	.147		.234	
1000	.131	45	.214	42
800	.111		.189	
600	.087	43	.153	42

T_4 is temperature of hydrogen before expansion.

The table illustrates the importance of having the temperature of high-pressure hydrogen leaving pot N2 as low as possible. Should the exchanger have a low efficiency, T_3 would be below T_1 and the efficiency of liquefaction would be greatly reduced.

APPENDIX D

CONSTRUCTION DETAILS OF PROBE

The probe (not shown) consisted of a 1/16" O.D. 24" length cupro-nickel tube with 0.010" wall, an electrical heater, and a thermocouple. The electrical heater consisted of about 60 turns of # 40 constantan wire, wrapped in three layers on the outside end of tubing. To the ends of the heater wire were soldered two leads of #32 copper wire, the joint being insulated with a thin coating of bakelite. The thermocouple was an exact duplicate of the thermocouple in liquefier with an addition of a coat of bakelite as insulation. The leads to the heater and the thermocouple were drawn through the tube by another wire. The end of the thermocouple is held inside the cupro-nickel tube 1/32" from the end by a loop of wire which passes between the two thermocouple wires. The ends of the loop were wrapped and tied around the heater. This maintained the thermocouple in stationary position.

APPENDIX E

TABLE III

DETAILS OF CONSTRUCTION OF COOLING COILS AND HEAT EXCHANGERS

OF HYDROGEN LIQUEFIER

Symbol	Description	Materials*	Tubing Outside Diameter in Inches	Tubing Wall Thickness in Inches	Length in Feet	Number of Turns	Diameter of Mandrel used for Winding in Inches	Final I.D. of coil in Inches
Cooling Coils								
F1	H.P. gas	copper	1/8	0.032	14	21	2-1/4	2-5/16
F2	H.P. gas	copper	1/8	0.032	5.3	8	2-1/4	2-5/16
Heat Exchangers								
E1	H.P. gas	copper	3/16	0.035	10	16	2-1/4	2-5/16
	L.P. gas	copper	1/4	0.032				
E2	H.P. gas	copper	1/8	0.032	9.5	14.5	2-1/4	2-5/16
	L.P. gas	copper	1/4	0.032				
E3	H.P. gas	Cu-Ni	1/8**	0.010	1.3	2	2-1/4	2-3/8
	L.P. gas	Cu-Ni	1/8	0.010				
X	H.P. gas	Cu-Ni	1/8***	0.010	2.5	4	2-1/8	2-9/32
	L.P. gas	Cu-Ni	3/16	0.010				

---

* All tubing was of "dead-soft" temper.

** Before flattening.

*** Before twisting.

TABLE IV

SPECIFICATIONS FOR PARTS OF HYDROGEN LIQUEFIER

Symbol	Description	Material	Tubing O.D. in Inches	Tubing Wall Thickness in Inches	Length in Inches
N1	Upper pot	Cu-Ni (h)*	3	0.042	15
N2	Lower pot	Cu-Ni (h)	3	0.042	3
K	N1 filling tube	Monel (h)	1/2	0.010	8
L	N2 vacuum line	Cu-Ni (h)	3/8	0.010	18-1/2
M	Expansion valve stem	Cu-Ni (h)	5/32	0.020	26
	Sleeve tube for stem	Cu-Ni (h)	3/16	0.010	25-1/4
O	Stem for NV	Cu-Ni (h)	5/32	0.020	16-1/2
	Sleeve tube for stem	Cu-Ni (h)	3/16	0.010	16-1/2
	Tube between N1 and NV	Cu-Ni (h)	1/4	0.010	1
	Tube between NV and N2	Cu-Ni (h)	1/8	0.010	1-1/2
HT	Hydrogen transfer tube				
	Vacuum jacket	Cu-Ni (h)	3/8	0.010	28-1/2
	Inner tube	Cu-Ni (h)	3/16	0.010	36-1/2
R	N1 exhaust	Cu-Ni (h)	3/8	0.010	

* The letters (a) and (h) refer to "dead-soft" and "hard-drawn" temper, respectively.

TABLE IV (cont.)

SPECIFICATIONS FOR PARTS OF HYDROGEN LIQUEFIER

Symbol	Description	Material	Tubing O.D. in Inches	Tubing Wall Thickness in Inches	Length in Inches
G3	Dewar vessel pressure	Copper (a)	3/16	0.032	2
W	Brass dome	Brass	4	0.065	4-3/8
None	Circuit for T1 and T2	Cu-Ni (h)	1/16	0.010	12
None	Conduct for T3 and T4	Cu-Ni (h)	1/16	0.010	17
J	Dewar vessel	Pyrex			
	Outer tube		100 (mm)	2.4 (mm)	30
	Inner tube		85 (mm)	2.4 (mm)	29

Figure 2

View of Hydrogen Assembly of Liquefaction, Showing Commercial Hydrogen Cylinders, Purifier, and Liquefier.

Figure 3

High-Pressure Hydrogen Gas Purifier

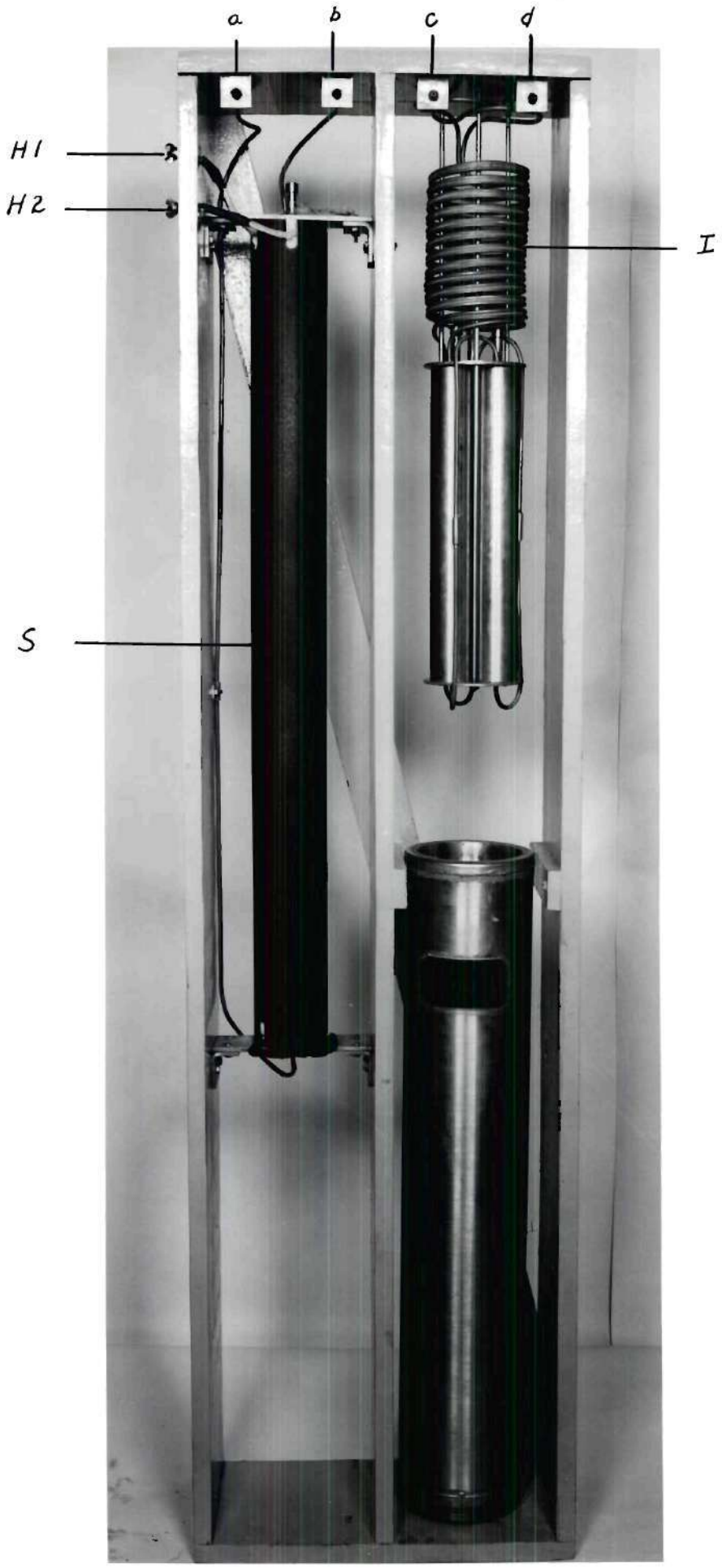
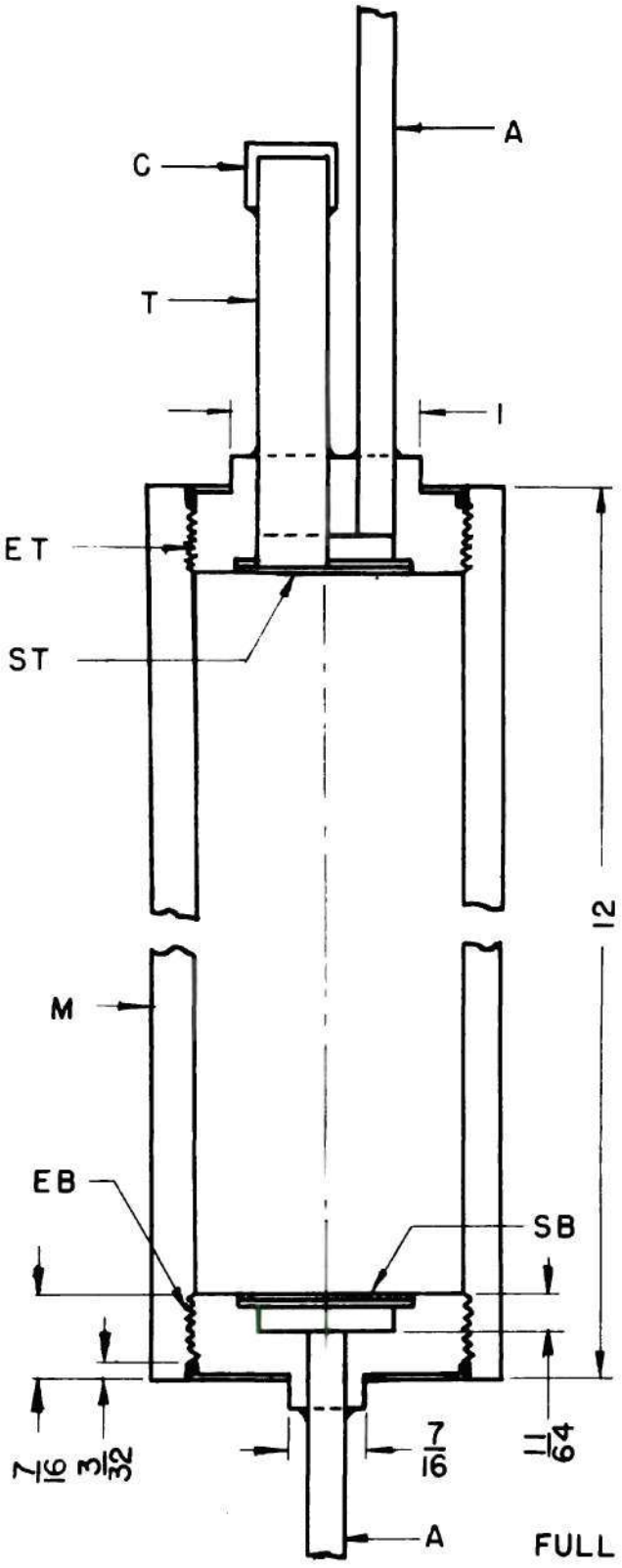

a
b
c
d
H1
H2
I
S

Figure 4

Details of Purifier Traps



DETAIL OF HIGH PRESSURE PURIFIER TRAPS

Figure 5

Liquefier (Rear View)

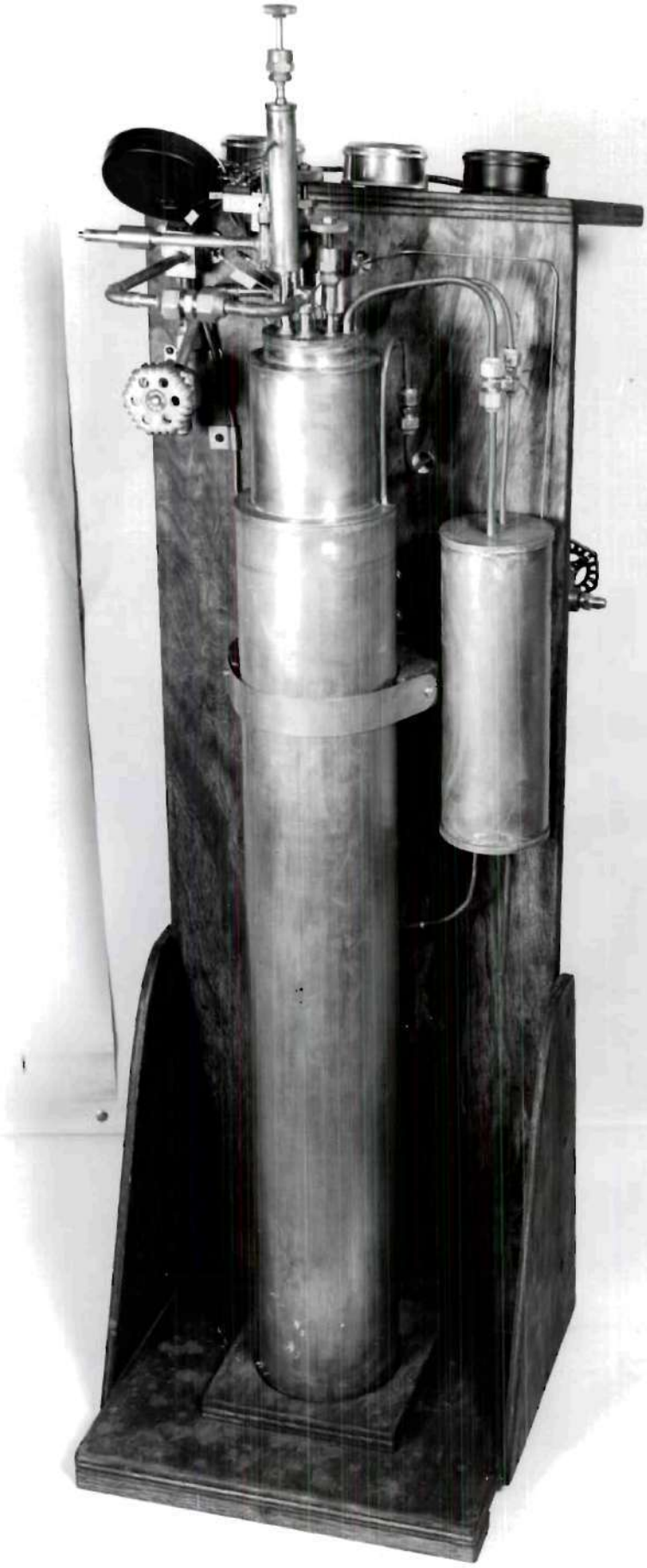


Figure 6

Control Panel of Liquefier

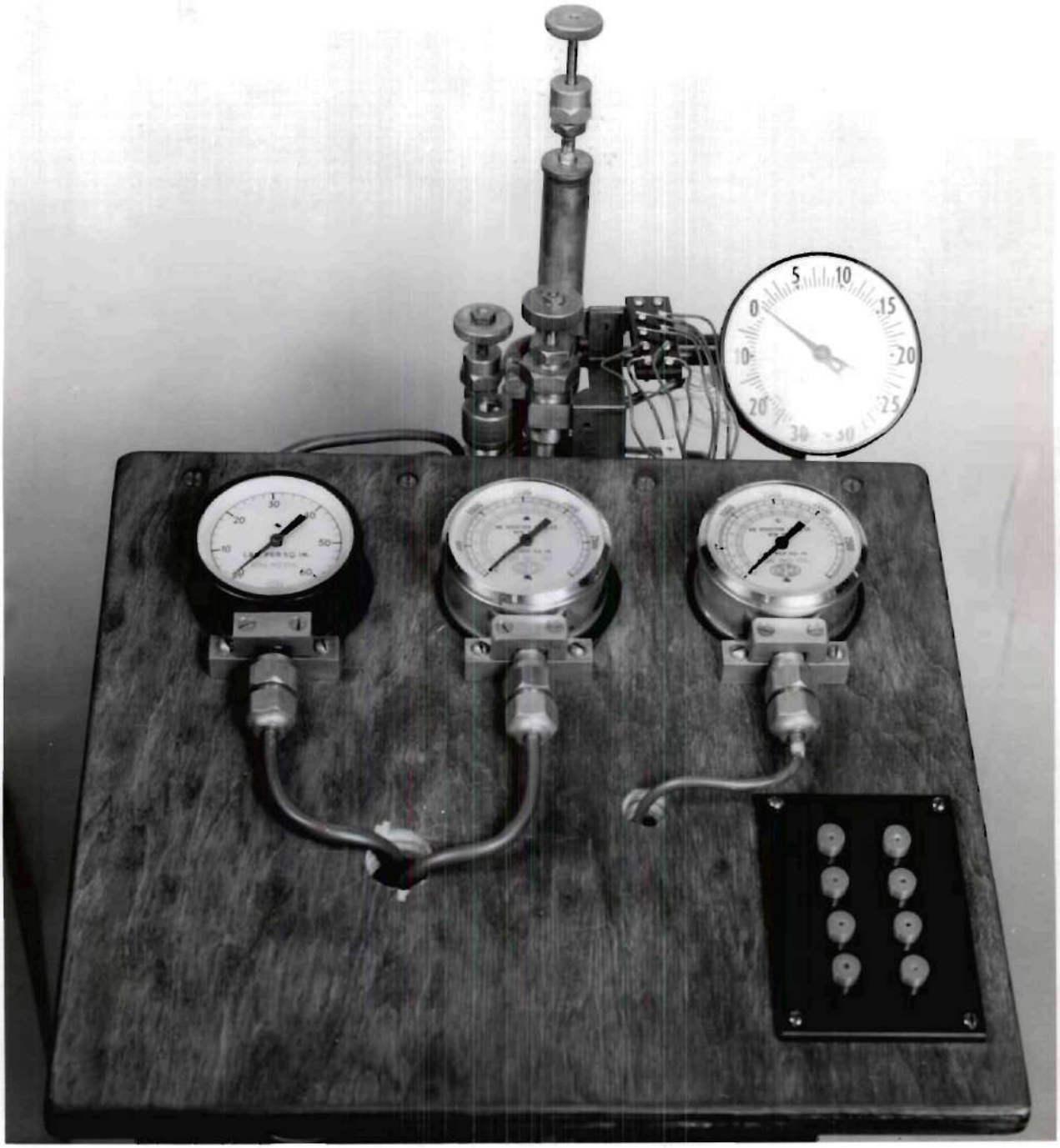

0
5
10
15
20
25
30
40
50
60

Figure 7

Liquefier Proper Removed From Brass Case

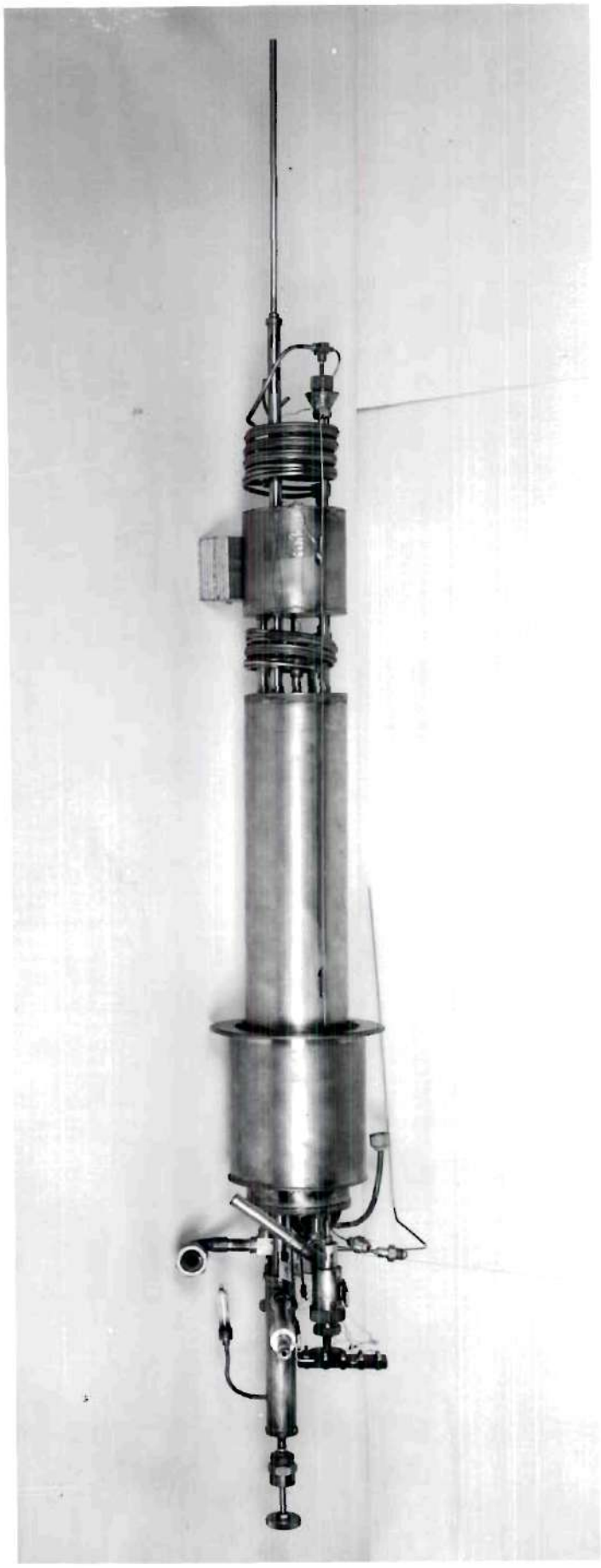
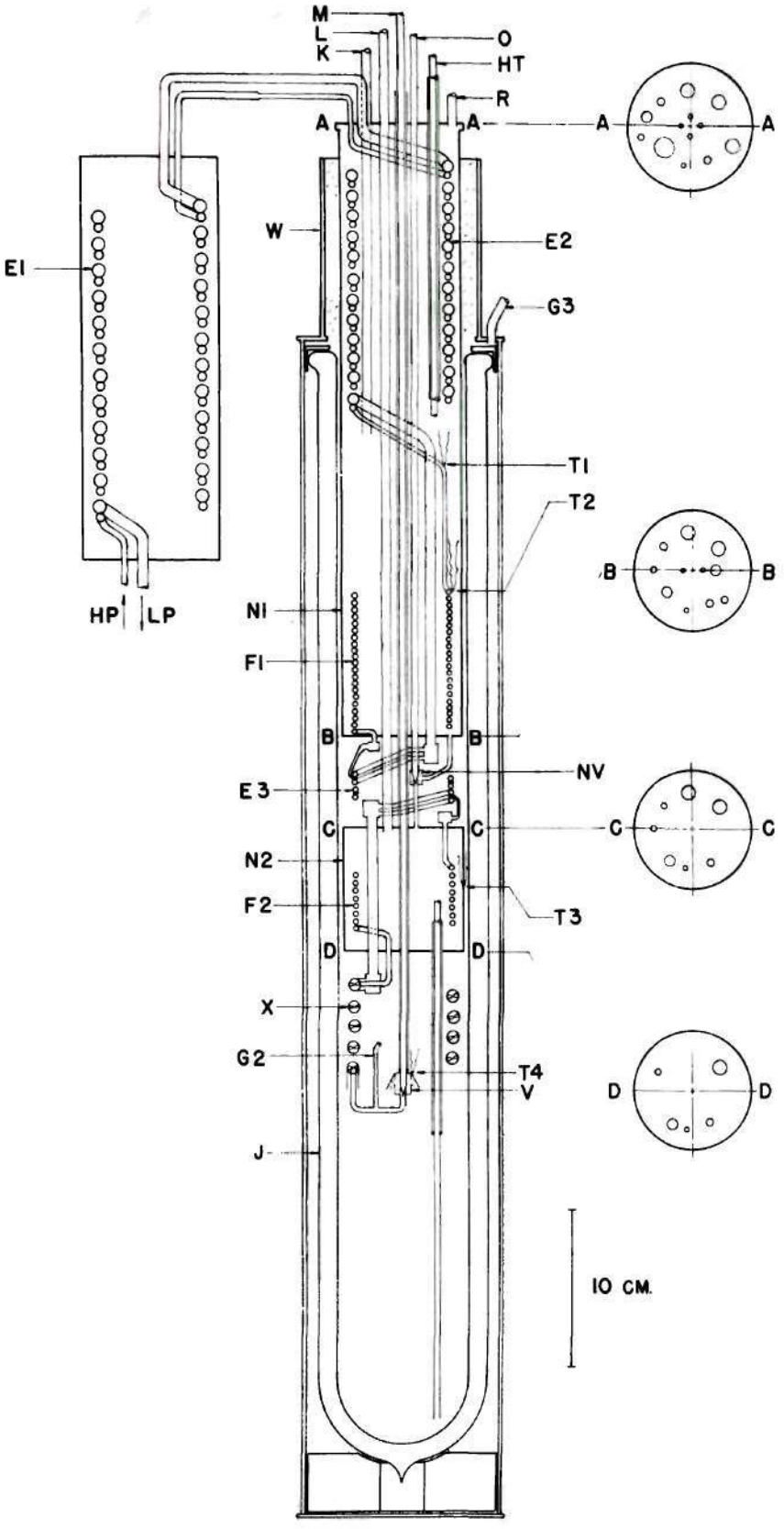


Figure 8

Schematic Detail of Hydrogen Liquefier



SCHEMATIC DETAIL OF HYDROGEN LIQUEFIER

APPENDIX F

Figure 9

P-V-T Relationships for Hydrogen[15]

A plot of PV product against temperature along constant pressure lines ranging from 1 to 200 atmospheres (PV = 1 at 1 atmosphere and 0°C.).

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[15] Deming, W. E., and Shupe, L. E., J. Am. Chem. Soc., 53, 843, (1931).

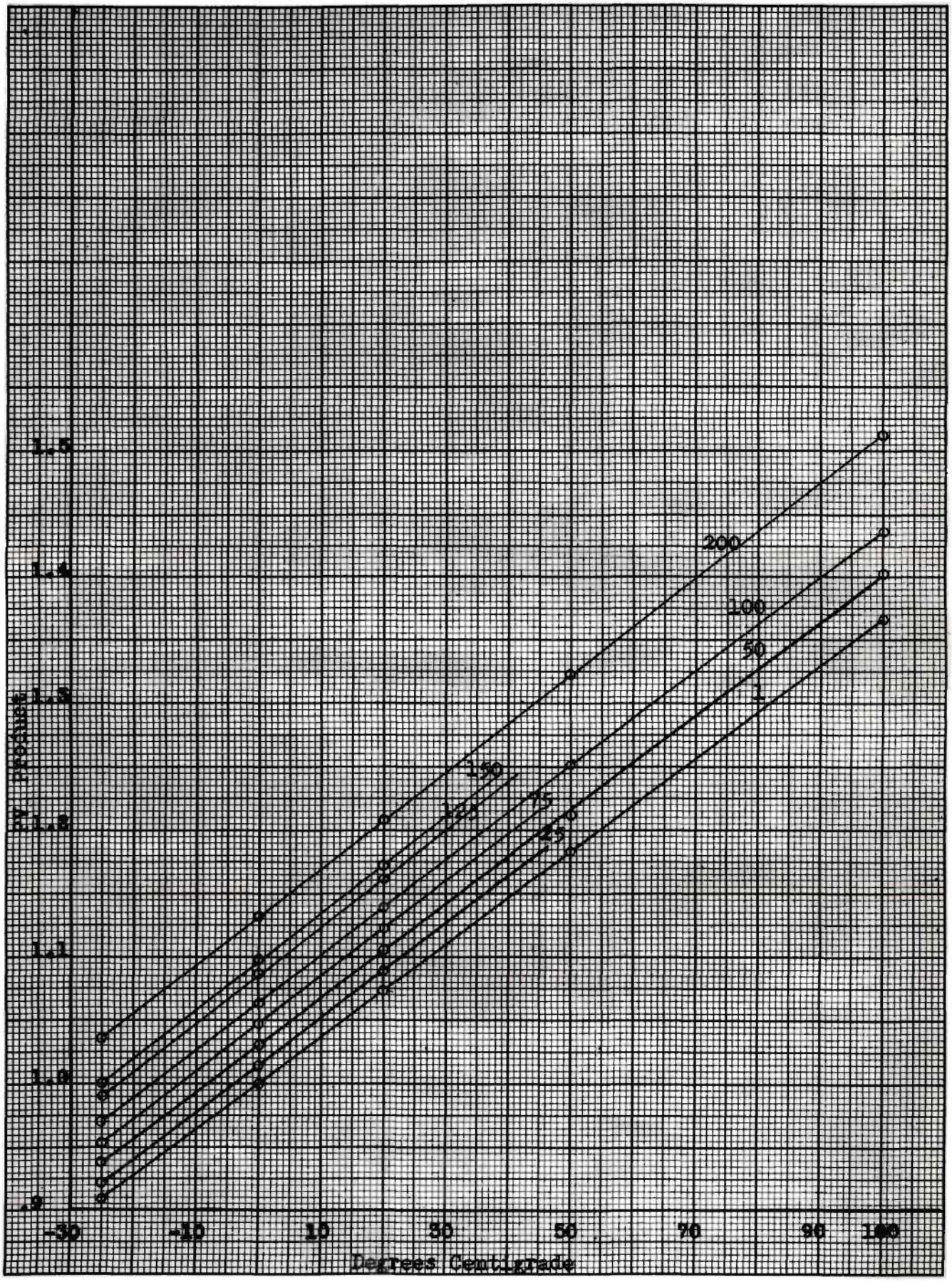
1.6
1.4
1.3
1.2
1.1
1.0
.9
Pressure
200
150
100
75
50
25
1
-30
-10
10
30
50
70
90
100
Degrees Centigrade

Figure 10

Volume of Hydrogen in Cylinder

A plot of pressure of hydrogen in cylinder (1.528 cubic feet) against volume the gas would occupy if measured at 25°C. and 1 atmosphere pressure. This curve was calculated using the data given in Figure 9.

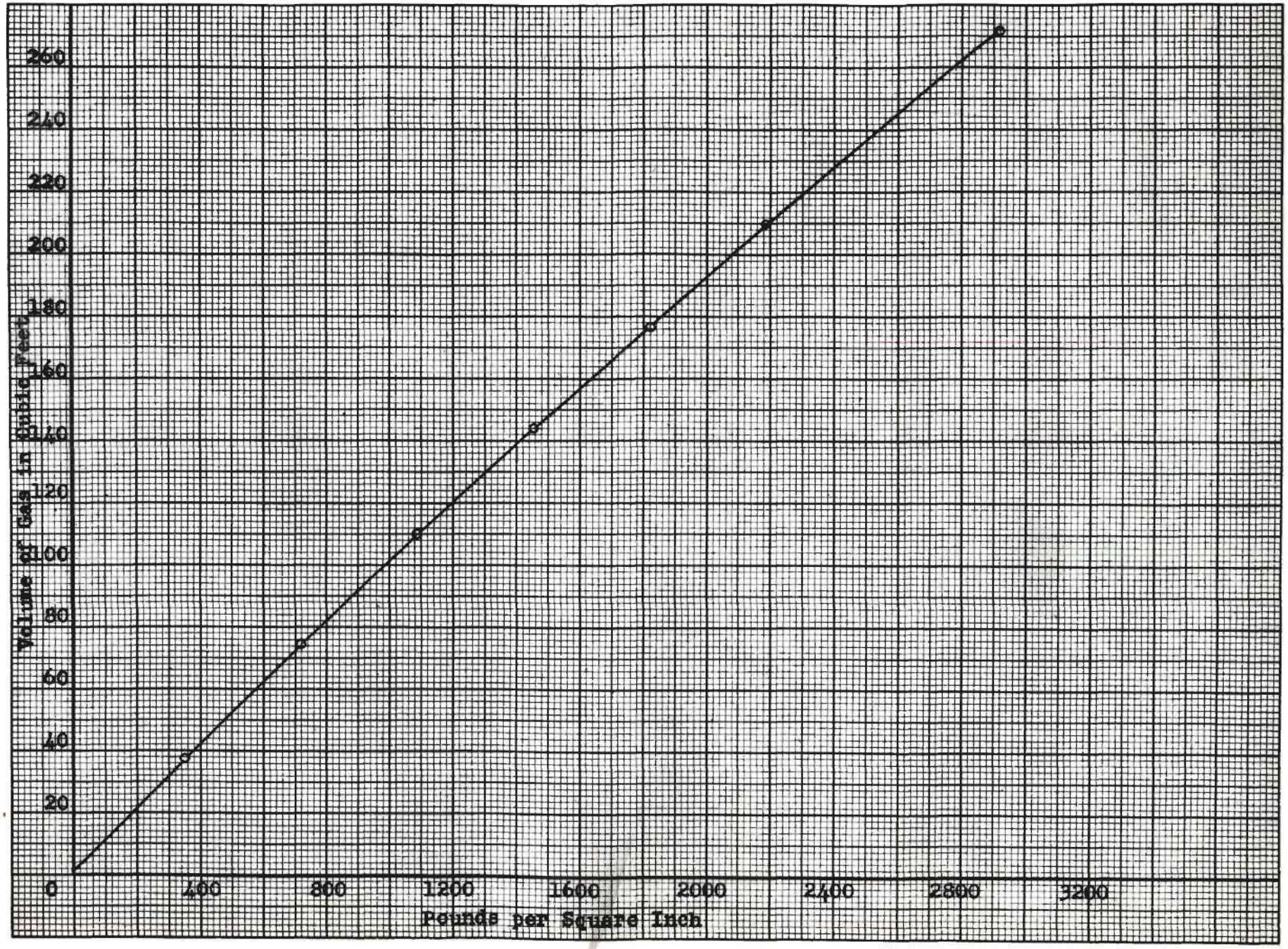
Volume of Gas in Cubic Feet
260
240
220
200
180
160
140
120
100
80
60
40
20
0
400
800
1200
1600
2000
2400
2800
3200
Pounds per Square Inch

Figure 11

Viscosity of Hydrogen

A plot of temperature in degrees Kelvin against viscosity in poise along constant one atmosphere pressure line.[16, 17,18,19,20]

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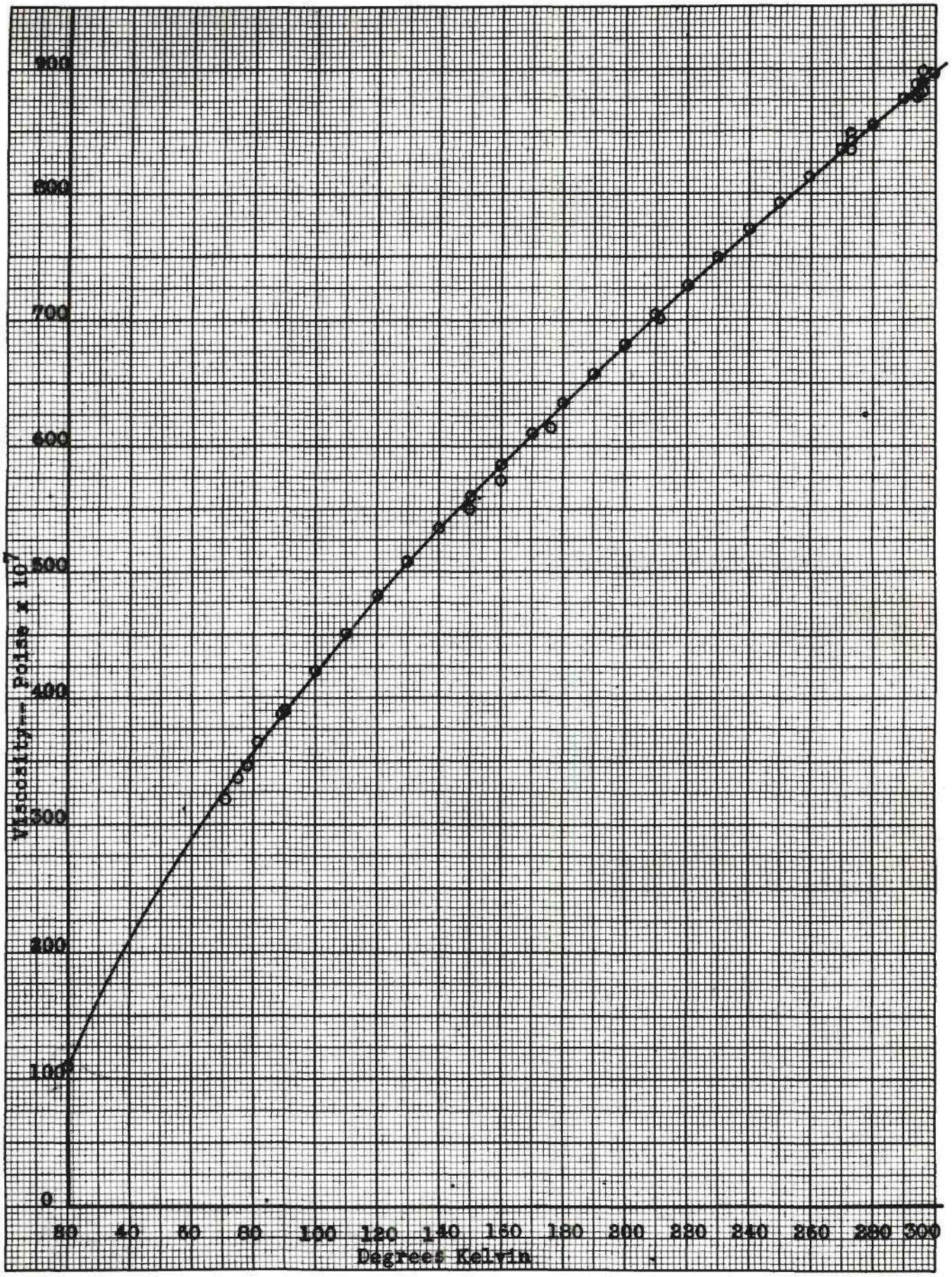
[16] Johnston, H. L., and McCloskey, K. E., J. Am. Chem. Soc., 44, 90, (1922).

[17] I.C.T., vol. I, 1, (1926).

[18] Landolt Börnstein, Physiklisch-Chemische Tabellen, Eg. I, 144, (1927).

[19] Ibid., Eg. IIa, 140, (1931).

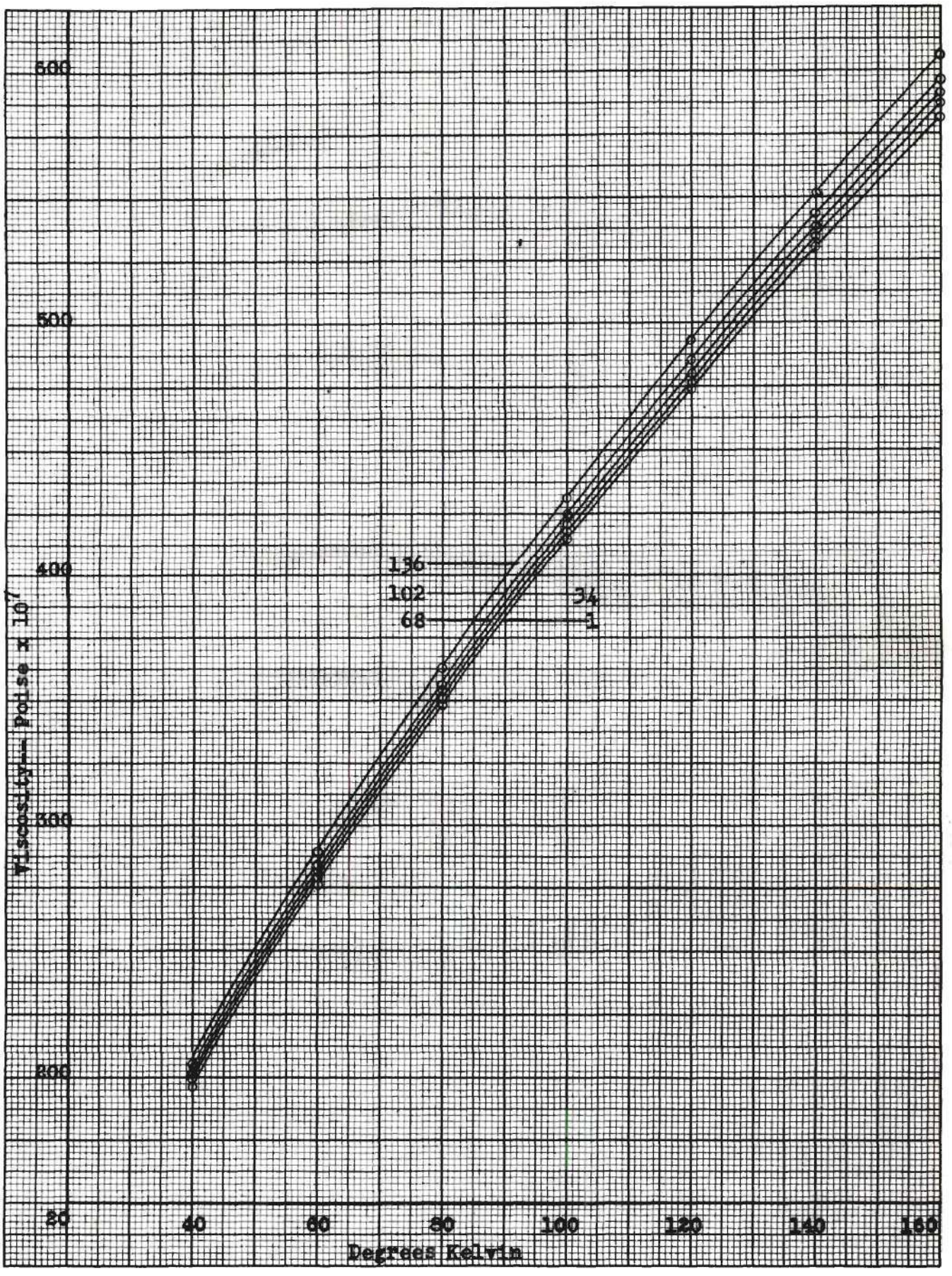
[20] Ibid., Eg. IIIa, 187, (1935).

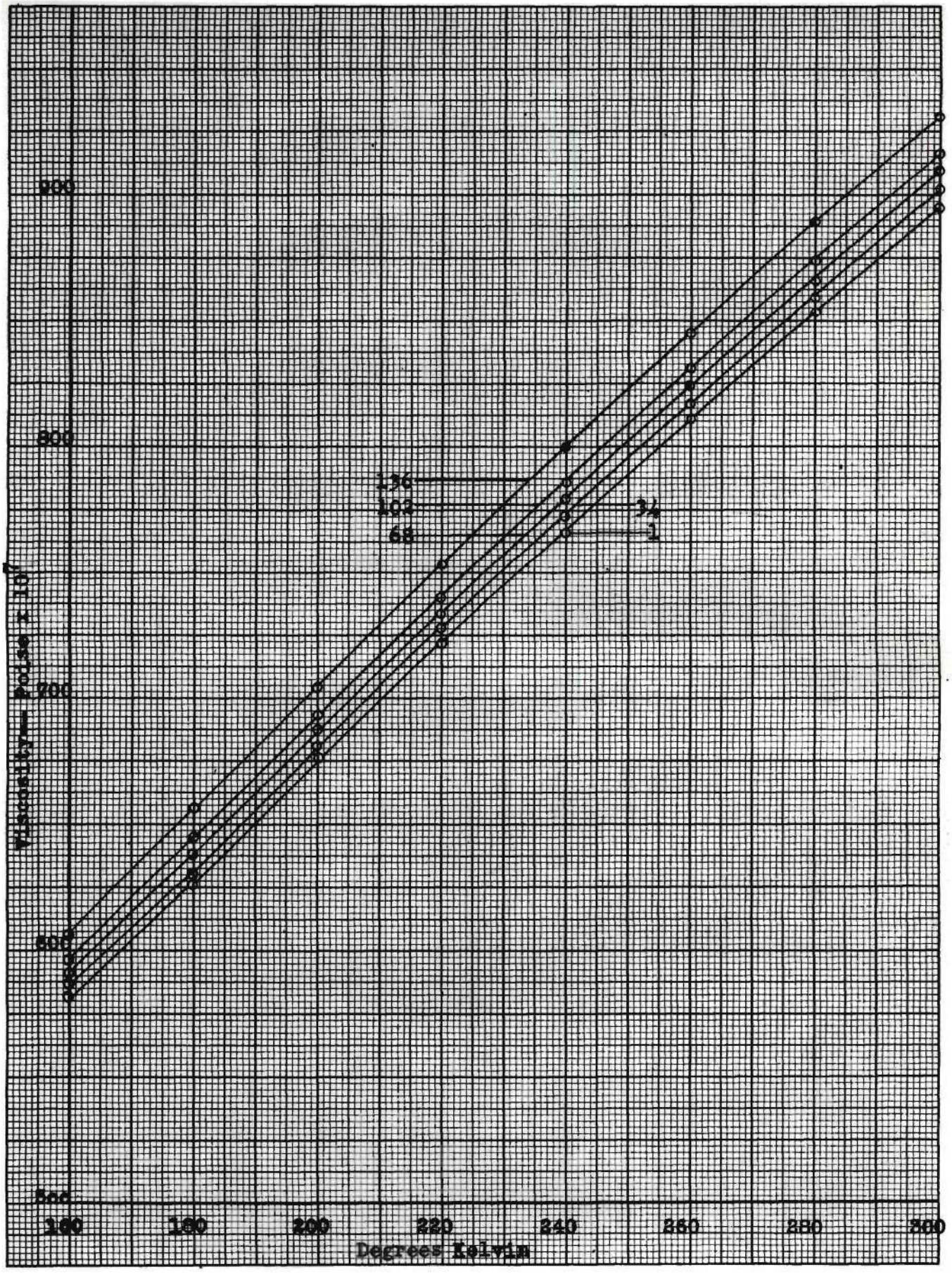

Viscosity - poise x 10^7
900
800
700
600
500
400
300
200
100
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
Degrees Kelvin

Figures 12 and 13

Viscosity of Hydrogen

A plot of temperature in degrees Kelvin against viscosity in poise along constant pressure lines ranging from 1 to 136 atmospheres.


600
500
400
300
200
136
102
68
3/4
1
Viscosity - Poise x 10⁷
20
40
60
80
100
120
140
160
Degrees Kelvin

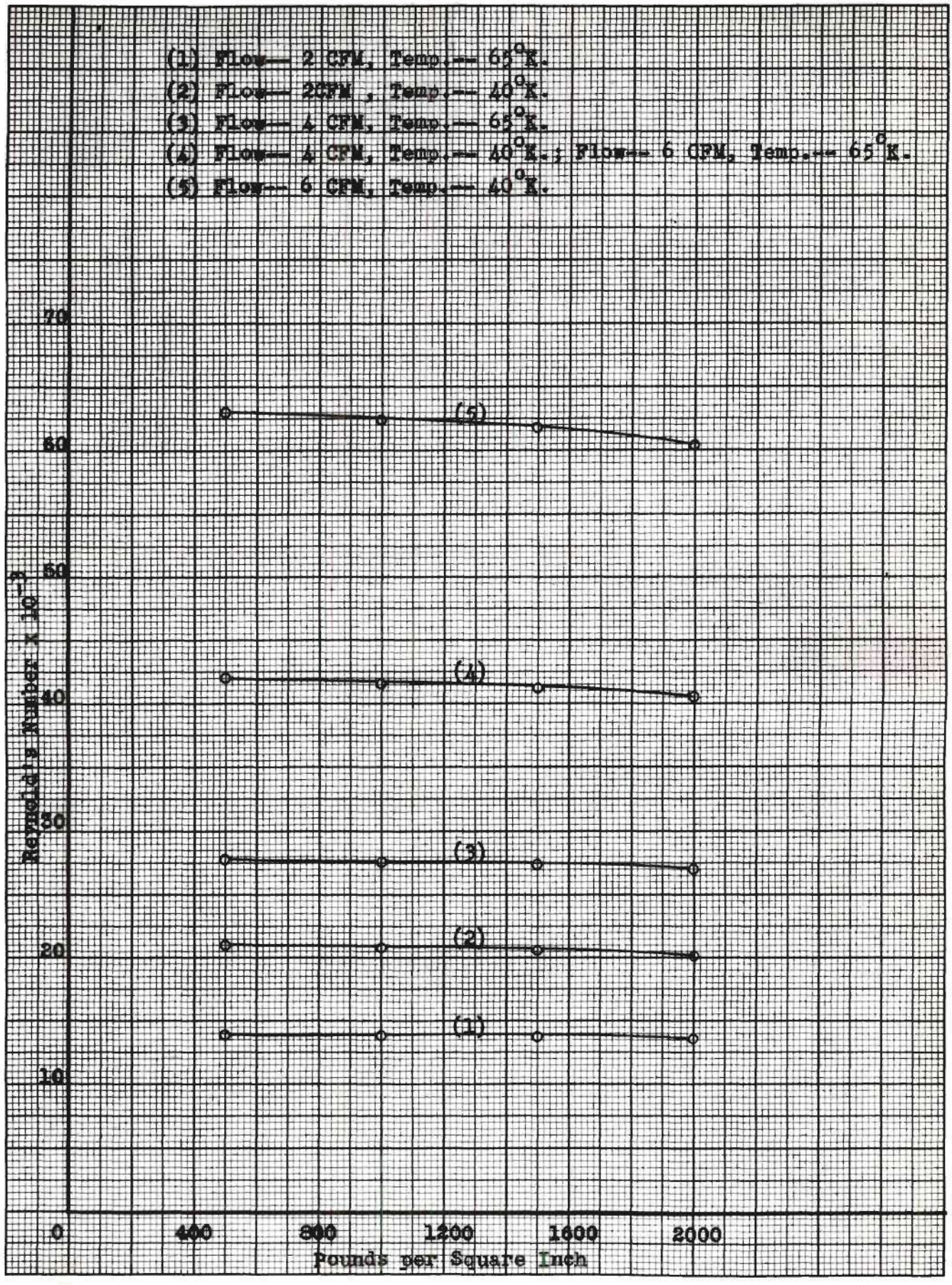

Pressure in mm Hg
900
800
700
600
500
136
102
68
34
1
160
180
200
220
240
260
280
300
Degrees Kelvin

The plot in Figures 12 and 13 were calculated by the method of approximate interpolation. This assumes that the viscosity of hydrogen changes at lower temperature with same relation that it does at the temperature of 25°C. As very little information could be found on viscosity of hydrogen varying with pressure, this method was used. The results seem to hold very well until temperatures below 30°K. are reached.

Figure 14

Reynold's Number

A plot of Reynold's number in high-pressure side of regenerative exchanger against pressure in pounds per square inch along jointly constant temperature and flow lines.

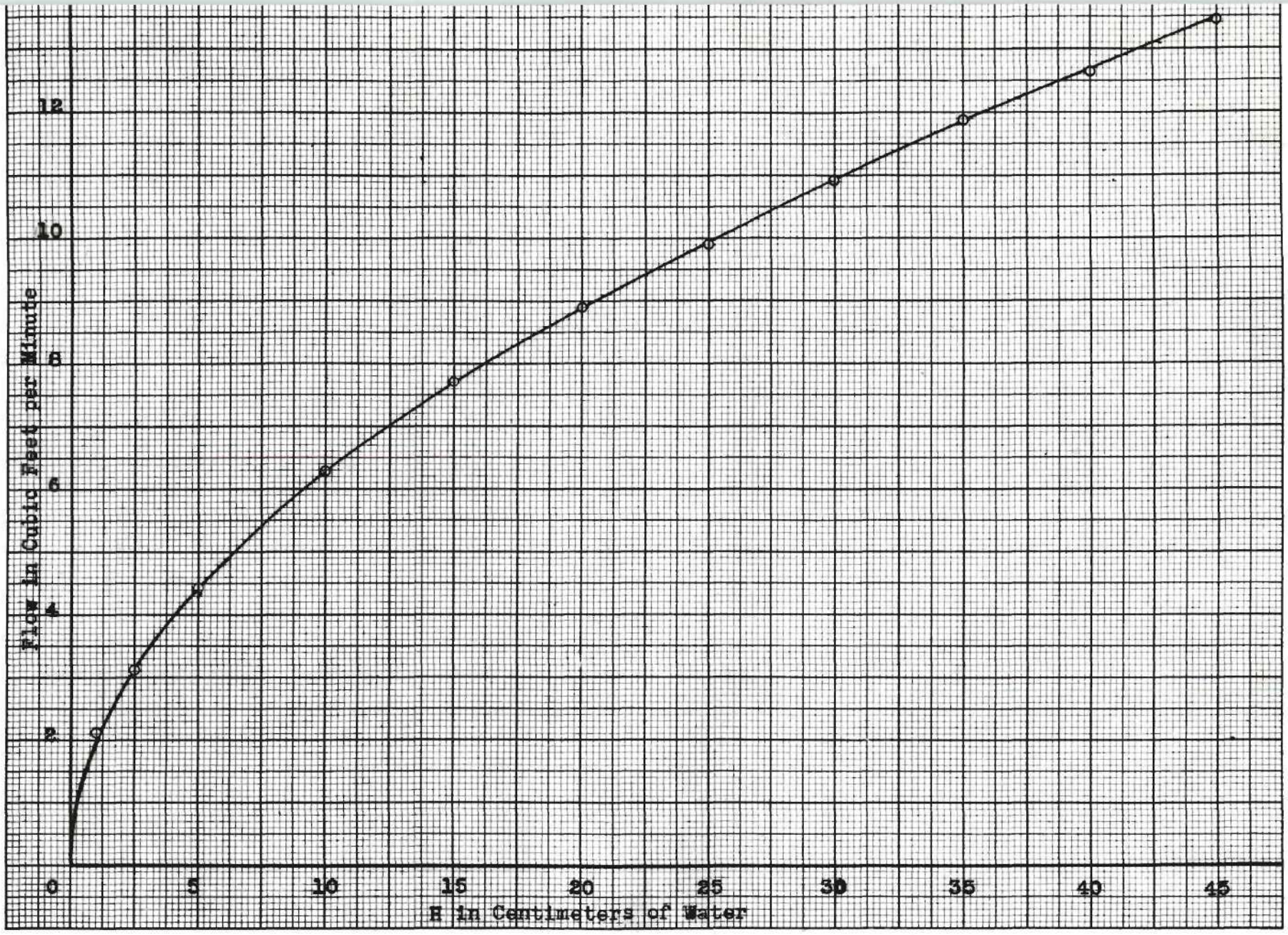

(1) Flow— 2 CFM, Temp.— 65°K.
(2) Flow— 2CFM , Temp.— 40°K.
(3) Flow— 4 CFM, Temp.— 65°K.
(4) Flow— 4 CFM, Temp.— 40°K.; Flow— 6 CFM, Temp.— 65°K.
(5) Flow— 6 CFM, Temp.— 40°K.
Flow x Cubic Feet per Minute
70
60
50
40
30
20
10
0
400
800
1200
1600
2000
Pounds per Square Inch

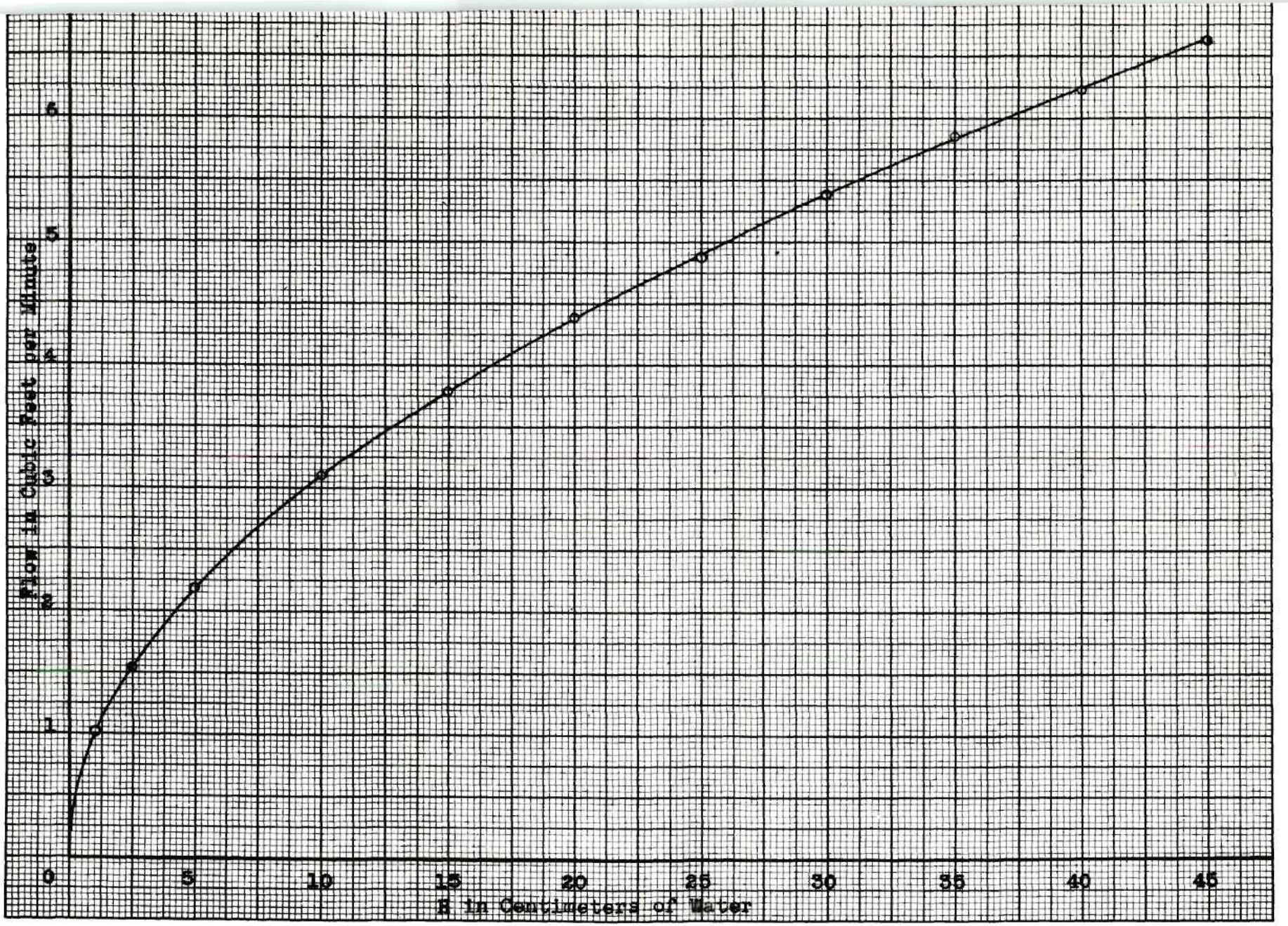
APPENDIX G

Figures 15 and 16

Calibration of Flow Meter

A plot of flow of hydrogen in cubic feet per minute against manometer differential in centimeters of water for orifices with drilled holes of diameter, respectively, .249 and .175 inches.


12
10
8
6
4
2
Flow in Cubic Feet per Minute
0
5
10
15
20
25
30
35
40
45
H in Centimeters of Water


Flow in Cubic Feet per Minute
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
H in Centimeters of Water

CALCULATION OF FLOW RATES THROUGH ORIFICE METER

Following Walker, Lewis, McAdams, and Gilliland[21] for flow of gases through orifices, this equation was obtained

$$q = 11.95 \times 10^4 C_v d_2^2 \sqrt{1 - P_2^{.288}} \qquad (4)$$

where q-- flow of hydrogen in CFM

C_v-- coefficient of discharge

d_2-- diameter of orifice in feet

P_2-- $(P_1 - P_h)$ in atmospheres

P_h-- height of manometer in atmospheres

P_2-- $(1 - .000967) \Delta H$ atmospheres

ΔH-- manometer differential in centimeters of water

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21 Walker, H. W., Lewis, W. K., McAdams, W. H., and Gilliland, E. R., Principles of Chemical Engineering, McGraw-Hill Book Company, Inc., New York and London, 56-68, (1937).